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Campaign on Remote Sensing of Plastic Marine Litter

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CONTRACT REPORT

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Acronyms

Cal/val Calibration and validation

FML floating marine litter

HDPE high-density polyethylene

NIR near infrared

PLP Plastic Litter Project

RE Red edge

RGB Red, Green, Blue

S2 Sentinel-2

SWIR short-wave infrared

UAV unoccupied aerial vehicle

VHR very-high resolution

1 Issue of marine litter and project overview

Marine litter consists of items that have been made or used by people and deliberately discarded or unintentionally lost in seawaters and on beaches, such as wood, metals, glass, rubber, clothing, paper, but in fact plastic debris is the most abundant marine litter (UNEP, 2005). Plastic products and thousands of plastic items break down into smaller pieces, called microplastics, through a combination of photodegradation, oxidation and mechanical abrasion (Andrady, 2011), whereas large thicker plastic items (i.e. macroplastics) can persist for decades especially when shielded from UV radiation under water or in sediments (Gregory & Andrady, 2003).

The Mediterranean Sea is the region of the global oceans with the highest amounts of municipal solid waste with 208-760 kg/person generated annually (http://www.atlas.d-waste.com, (Galgani et al., 2014)). Debris densities may increase by up to 40% in the summer months due to the high numbers of tourists who generate more than 75% of the annual waste during the summer season (Grelaud & Ziveri, 2020). A recent study estimated that the total plastic accumulated in the Mediterranean is estimated in the order of magnitude of 1,178,000 tonnes, with an uncertainty ranging from 53,500 to 3,546,700 tonnes. Of this amount, between 800 and 23,000 tonnes of plastic would be floating over the surface of the entire Mediterranean basin (Boucher & Billard, 2019). However, it must be pointed out that large uncertainties still remain on the total mass of debris entering the marine environment every year.

Remote sensing has the potential to contribute in filling the marine litter knowledge gap, with satellite remote detection of floating marine litter being an emerging field. There is, however, a constant need for high-quality *in situ* validated data.

Towards this goal, this project aimed at the production of a high-quality calibration and validation dataset for the remote detection of floating marine litter aggregations. The main data are comprised of Sentinel-2 images of artificial floating marine litter targets, essentially acting as in situ validated data. The resultant spectral information includes the spectral response of floating HDPE, wooden materials and a mixed material configuration (HDPE and wood). Additionally to Sentinel-2 imagery, the acquired data include very-high-resolution hyper-spectral data in the 400 to 100 nm spectral range acquired by a UAS-borne sensor (BAYSPEC OCI-F HYPERSPECTRAL IMAGER), in situ field spectrometer measurements in the 400 to 900 nm range and very-high-resolution UAS RGB images. These data are compiled into an online repository for easy access by the marine debris scientific community. Additionally, we have produced a spectral classification workflow using a partial unmixing methodology with the ability to successfully detect floating marine litter aggregations of at least as low as 20% coverage of a 10x10 m Sentinel-2 pixel.

The project is realized in the Island of Lesvos in Greece by a consortium with multidisciplinary expertise, including the Marine Remote Sensing Group from the University of the Aegean, the Institute for Marine Research from the National Research Council of Italy (CNR – ISMAR) and AS Prote Maritime Ltd.

1.1 Project Objectives

The project was divided into two main phases. The first year of the project was dedicated to target development and the selection of a characteristic reference material to be used in the FML targets, as well as all the licensing and approvals needed for the long-term acquisition campaign, while the second year of the project was the actual acquisition campaign with construction and deployment of the newly developed circular long-term deployment targets and the subsequent analysis of the obtained dataset.

The main project objectives were:

1. To develop long-term deployment targets for extended acquisition campaigns that would not require re-deployment for each satellite overpass.
2. To assess the suitability of different proposed items to be used as representative reference target materials.
3. To acquire the spectral response of a 10x10 m Sentinel-2 pixel that is full covered by the target materials, including the FML reference target material, a wooden target material approximating natural floating debris aggregations and a mixed target configuration.
4. To run a long-term data acquisition campaign during the Summer-Autumn period of 2021 and acquire a range of data including Sentinel-2 and high-resolution UAS data.
5. To assess the effects that environmental factors such as biofouling, submersion depth, turbidity and wind speed have on the spectral response of FML.
6. To assess the capability of remote detection of floating marine litter with partial unmixing methodologies using the Sentinel-2 satellite.

2 Project Summary

The next section outlines the main experimental field work that was done throughout the duration of the project, by providing a short summary of first- and second-year activities.

2.1 First year activities

During the first term of the project, a significant effort was put into the development of new target designs that could be used for long-term deployment, exploring the use of circular targets instead of rectangular ones, based on the experience gained through previous projects (Topouzelis et al., 2019, 2020). A series of test deployments and data acquisitions were performed. These were done to allow for the development, while assessing the performance and durability, of the newly designed circular targets. For the first months of the project, much effort was put towards the construction of new target prototypes, in the attempt to move from the model of target re-deployment for every acquisition date, to a more long-term deployment model. Such an approach reduces day-to-day logistics and allows for a greater number of acquisitions under variable conditions.

Two different sub-types of circular targets were constructed and tested during the summer of 2020: an aquaculture cage-type target (fig. 1) and a single-ring target (fig. 2). The circular shape of the targets was chosen for increased durability and to allow the use of HDPE pipes instead of PVC. HDPE

has a higher modulus of elasticity and is much more resistant to cyclic loading than PVC. In addition, HDPE pipes allow the use of compression fittings, which make it possible to disassemble and reassemble the target frame with ease. The main disadvantage of HDPE compared to PVC is cost, with HDPE being much more expensive.

Test deployment results showed that the aquaculture design can be successfully used to accommodate various marine debris types, of both anthropogenic and natural origin. Some grouping of materials was observed due to wave action, but the effect was not sufficient to present issues, as the materials would flow back with the trough of the wave. However, in order to assure that no loss of materials would occur during long-term deployment, it became evident that the use of high-quality professionally made aquaculture cages would need to be used. After receiving several quotes from various aquaculture manufacturers, we established that the cost for such targets would be too high and hence the development of this type of targets was put on hold.

Figure 1: Aquaculture-cage type target test deployment for buoyancy assessment.

Figure 2: Single-ring 7 m diameter targets during test deployment

The single-ring targets are made of a single HDPE ring, with two different variants, both 7 m in diameter produced. For the first variant, in order to deploy characteristic marine litter items, we added a bottom and top net, with the litter retained in between the two nets, essentially creating a sort of sandwich-like structure. Much like the cage-type target, the materials were floating freely inside the HDPE ring, retained solely by the fishing net surrounding the frame (fig. 2). The main

disadvantage of this target is the increased effort needed in order to replace the materials, since the net has to be removed and the materials need to be collected outside of the water. The second variant of this type of target was a single ring with a white HDPE mesh attached, which can be considered a representative material for plastic marine litter (being PE items among the largest fractions of marine litter items).

The white HDPE mesh was selected after spectral comparison and through a grade-based process to be used as a main target material and incorporates a series of advantageous characteristics. Other materials that were considered included shade balls, buoys, 4L containers and tarps, all made of HDPE. The HDPE mesh is a well characterized material, with known manufacturing properties that can be well defined; it has a density of 0.955 gr/cm^3, it is produced through extrusion and is coloured using an HDPE based, food safe paint at a 0.8% ratio. Hence, it can be used as a reference material in different studies from different research institutions, implementing various measuring systems from satellite imagery, to UAV, to field and lab spectrometry. It is produced in a variety of colours, it is a resilient and robust material and its use ensures that no loss of material to the environment will occur. Its durability and relative resistance to UV radiation make it a good candidate for longer-term deployments. Figure 2 shows a 7 m diameter white HDPE mesh target deployed off Tsamakia Beach.

In addition to the circular targets, during the first year of the project we developed a set of inflatable, reusable targets that will be deployed during the PLP2022 acquisition period. These targets can be populated by different FML materials that can float freely inside the target area. The main aim of these targets is the ability for them to be readily transferred and used in variety of data acquisition campaigns, from different research groups and interested parties.

2.2 Second year activities

Second year field activities revolved around the construction, deployment and data acquisition of the long-term-deployment HDPE mesh and wooden targets. The next sections outline the work done during the spring, summer and autumn of 2021.

Figure 3: Left: Concrete anchoring blocks at the curing stage. Right: Large volume surface buoy with attached light and note with information about the experiment.

The design and deployment of the target anchoring system was a pivotal part of the campaign design. The anchoring system was composed of a set of 6 concrete anchoring blocks, connected to 6 large-volume surface buoys, on which the long-term deployment targets are tethered on (fig. 4). The buoys were equipped with lights visible up to 4 nautical miles as per specifications of the Greek nautical law. The system needed

to be designed as such that it would be sufficient for retaining the large-area targets in place with minimal translation, in order to comply with the area restrictions relevant to the licencing of the project and to avoid damage to the targets. Additionally, the system, and specifically the size of the concrete blocks, was designed to minimise the environmental impact and more specifically the blocks sea bottom footprint.

Target construction was performed at a site near the deployment area. The targets were prepared on land, assembled on the nearby beach, transported to the deployment area and tethered to the surface buoys. A total of more than 25 student volunteers, PhD candidates and researchers worked on the target construction, which took place at an old fuel pumping station. A ≈28 m diameter white HDPE mesh target was constructed for long-term deployment during the PLP2021 data acquisition campaign. The size of the target was such that ensured that a 10x10 m Sentinel-2 pixel would be fully covered by the target regardless of target orientation in the image pixel grid. It also allowed for relevant measurements in the 20 m SWIR and Red-Edge (RE) bands of the Sentinel-2 sensor. The HDPE mesh is a robust material, that when deployed at sea has an overall coverage rate of about 30% and produces a spectral signature almost identical of FML concentrations, based on comparisons made with realistic FML targets. The construction of the target was a challenging process, requiring a well thought-of workflow and good cooperation between the construction team members. A wooden planks target representing another common type of floating debris was constructed out of 4 m long and 22 cm wide planks. The planks were tethered together in groups of 9 planks with 30 cm gaps in between each plank.

Figure 4: HDPE mesh and wooden planks targets deployed.

Deployment of the targets took place during June 2021. The HDPE target was pre-assembled in shallow waters at the beach under the area where the works took place. During deployment, the target was slowly towed from its assembly position towards the deployment area using two inflatable boats. Deployment of the wooden planks target was more challenging since the target could not be pre-assembled at the construction area. The wooden planks were transported to the deployment area in groups

Figure 5: Mixed target configuration.

and assembled in place. In order to produce a mixed material target, the HDPE mesh and wooden planks targets were combined into a single target. The wooden planks were positioned under and attached onto the HDPE mesh, effectively covering part of the gaps created by the HDPE mesh holes and reducing the water abundance fraction of the Sentinel-2 pixel (fig. 6).

3 Data acquisition summary

The PLP2021 data acquisition campaign took place during the summer and autumn of 2021. The main data acquired were a series of 22 high-quality cloud-free Sentinel 2 multispectral images of the target deployment area. Additionally, data acquisition included: very-high-resolution RGB images using a DJI Phantom 4 RTK, hyperspectral data in the range of 400-1000 nm using a Bayspec OCI-F Hyperspectral Imager on board a UCD S-1000 hexacopter, *in situ* hyperspectral measurements in the range of 400-900 nm using an Oceanview spectrometer and ancillary data including wind speed and direction, light intensity and water turbidity using a Secchi disk. Data acquisition took place every 5 days, in tandem with Sentinel-2 acquisitions. A small boat was used for the acquisition of *in situ* measurements and ancillary data, as well as the inspection of the targets and the carrying out of any repairs needed. A total of 22 high-quality cloud-free images of the deployment area were acquired during the PLP2021 data acquisition campaign. The data acquisition period spans from the 11th of June 2021 to the 4th of October. The large amount of data acquired allows for a comprehensive spectral analysis of the HDPE mesh, wooden and mixed target signatures. Additionally, the long-term deployment of the targets presents the ability to assess the effects of biofouling, submersion depth and wind speed and turbidity on the spectral response of FML.

Figure 6: Sentinel-2 true colour RGB composite of the study area acquired on 20210626 showing the HDPE mesh/FML target (top) and wooden planks/natural debris target (bottom).

Hyperspectral data were acquired in tandem with Sentinel-2 acquisitions in 3 separate dates: 20210716, 20210731 and 20210830. The hyperspectral data are organised in data cubes for each data acquisition day. Each target is depicted in a separate data cube to minimize the overall data size. The data can be used to compare reflectance values with Sentinel-2 data to assess the effectiveness of atmospheric correction processors such as ACOLITE. The high spectral resolution of the hyperspectral imager can offer a significant insight into the spectral signature of the target materials.

On each Sentinel-2 acquisition we performed a simultaneous UAV flight acquiring a series of very high resolution RGB images of the study area. The images are used for aerial inspection of the targets and for dissemination purposes. Additionally, a series of nadir-viewing, overlapping images are acquired to produce very high resolution orthophoto maps of the study area for each acquisition date. These maps are overlayed on top the Sentinel-2 image pixel grid and allow for the approximation of the target abundance fraction in each Sentinel-2 pixel.

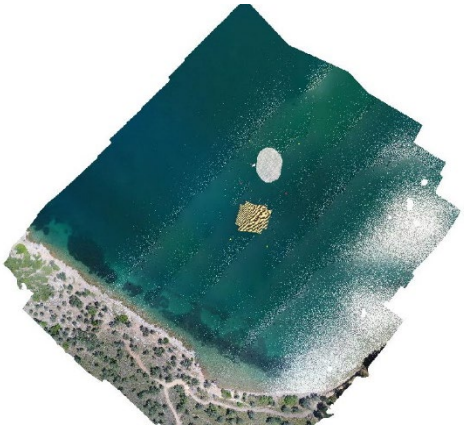

Figure 7: 20200626 orthophoto map of the study area showing both targets.

Several spectrometer measurements were carried out *in situ* on Sentinel-2 acquisition dates. The measurements were carried out either right before or right after the Sentinel-2 acquisition to minimise any difference in conditions during the two acquisition stages, including sunlight incident angle, wind speed and atmospheric conditions. The spectrometer measurements were extremely difficult to be performed in a consistent manner due to the format of the instrument and the boat movement.

In addition to the Sentinel-2, UAV and *in situ* spectrometer data, a series of ancillary measurements were performed on each acquisition date. These included wind speed and direction, light intensity and water turbidity using a Secchi disk empirical measurement. A relative biofouling accumulation assessment was also performed on each acquisition date, along with a record of the state of the targets (floating/partially submerged/submerged). These ancillary measurements add value by allowing for the assessment of the effect that different parameters and environmental conditions have on the spectral response of the targets and consequently on FML concentrations under real conditions.

Figure 9 presents the mean spectral profile of the HDPE target, the wooden target and the mixed target, comparing these to verified FML concentrations and other surface features. The HDPE spectral plot shows a generally flat signature from the blue to NIR wavelengths, with a marginal peak in the green band. This is especially evident when not considering the SWIR bands of the MSI. The RGB and NIR bands show practically the same reflectance at about 0.08. The 3x3 averaged mean signature is almost fully flat with marginal variation between the different band responses. The wooden planks target response, contrary to the HDPE mesh, presents an upwards slope from the blue to the NIR wavelengths. This response is generally characteristic of dry, non-photosynthetically active vegetation or woody materials. The mixed target has an intermediate response, with a spectral shape that should in theory be possible to approximate with a linear mixing expression. The PLP2021 targets

have almost identical spectral features with the debris pixels from validated occurrences in Haiti (Kikaki et al., 2022), with spectral angles showing great similarity. Subsequently, we can see that other surface features such as sea snot (2021 outbreak mainly originating in the Sea of Marmara), pollen (recent surface accumulations around the island of Lesvos in April 2022) and ship wakes can have significant implications with regards to FML detection. All these surface features have spectral shapes very similar to those of FML. Hence, for discrimination between FML and other surface features, FML detection methodologies need to take these spectral similarities into account.

One of our main goals for PLP2021 was the assessment of the effects that a set of parameters have on the spectral response of FML. An effort was made to assess the different parameters individually and independently. For this reason, to the extent that it was possible, we have categorised the data based on the conditions during acquisition, and have isolated these in order to account for only the parameter under investigation (e.g. to assess the effects of biofouling on the target signatures we do not examine data in which the target was also partially submerged under the water surface and vice versa). The main parameters that we have investigated include degree of biofouling, submersion depth and turbidity.

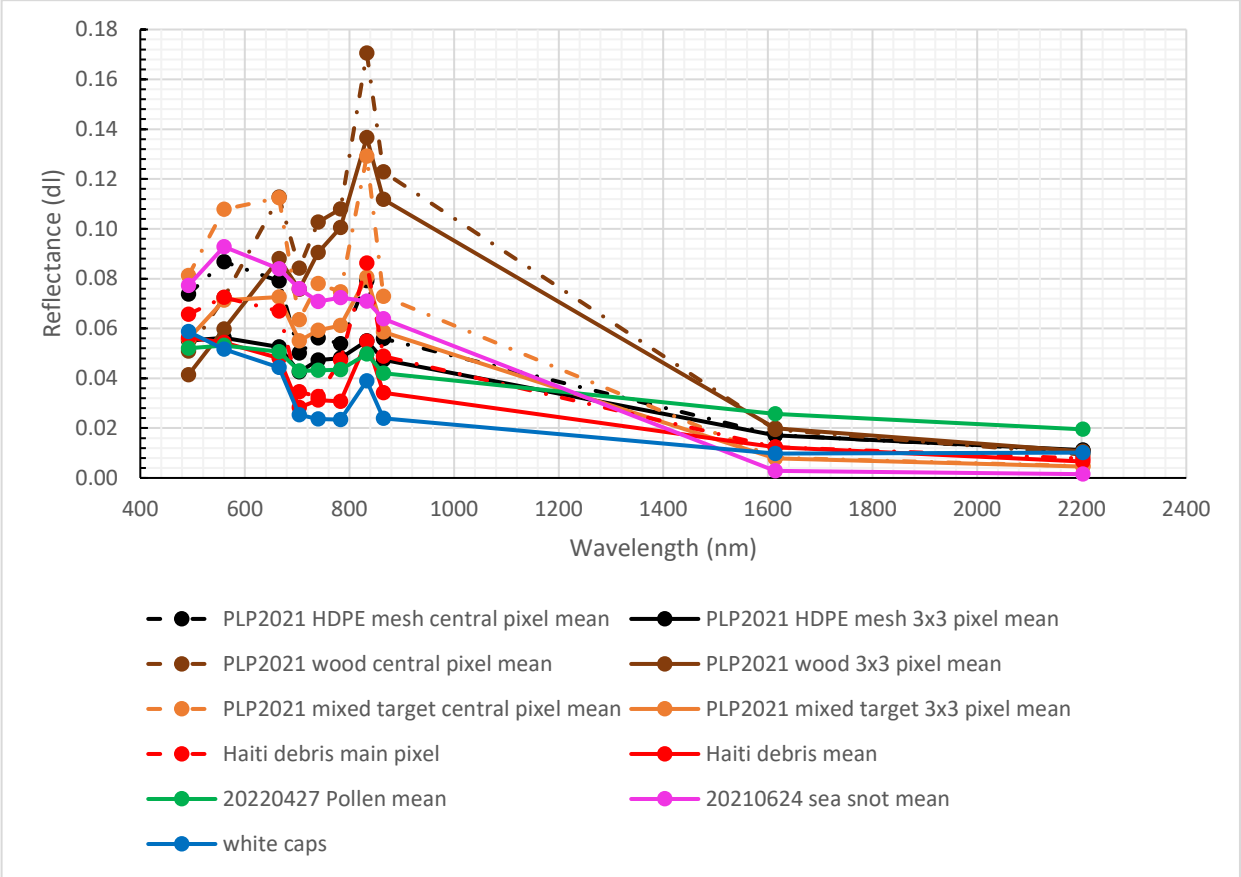

Figure 8: TOP: Comparison of PLP2021 spectral plots with, Haiti debris and other surface features. BOTTOM: Central pixel mean values and 3x3 averaged mean of all PLP2021 targets. Main pixel mean and averaged mean of debris pixels from La Gonave Island, Haiti (source: Kikaki et al, 2022).

4 FML detection results

FML detection is performed by a matched filtering algorithm. The algorithm works by performing a partial unmixing using a specified spectral signature as the endmember of interest – in our case the mean HDPE signature acquired during the PLP2021 acquisition campaign, suppressing the background signals. Any number of available bands can be used based on their relativity given the specific application. Here we use two different band combinations: one using the four 10 m Sentinel-2 RGB and NIR bands and one using also the 20 m red-edge, NIR and SWIR bands. The two different band combinations are used to detect the maximum possible number of pixels (4 band combination) and also to discriminate between plastic FML and other floating matters (such as the wooden target) and minimise the number of false positives (10 bands combination).

Figure 10 presents the detection results after a cumulative binary threshold has been applied on the matched filtering results from 20210621. Five out of the nine HDPE target pixels are effectively detected, although the pixels that are not detected have abundance fractions that are quite less than 20%. It is possible to increase the accuracy of detection, however the applied thresholds are set so that the number of false positives is greatly reduced. In order to assess the effectiveness of the detection methodology under natural scenarios, the algorithm was applied on verified FML

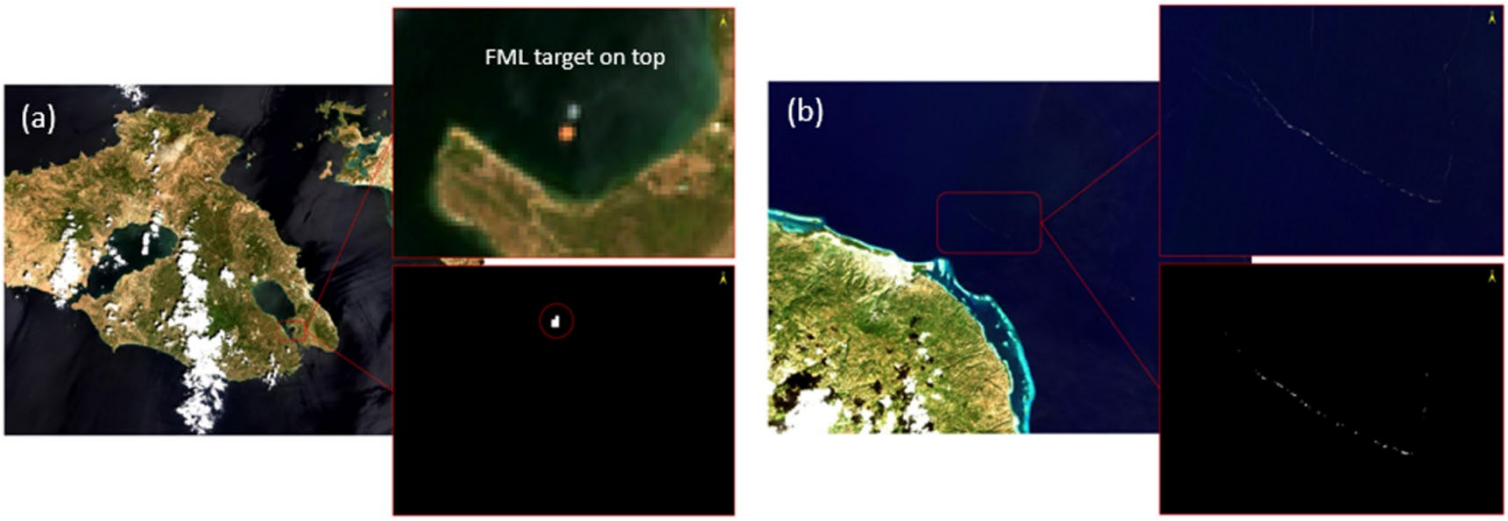

Figure 9: Detection workflow results. A. FML targets detection results from 20210621. B. FML windrow detection from La Gonave island, Haiti in 20202212 (source of S2 image: Kikaki et al, 2022)

aggregations. Figure 10 also shows the detection methodology applied on validated FML concentrations off the coast of La Gonave Island in Haiti. The applied methodology can effectively be used to detect many pixels from the FML windrow with a small number of omission errors.

5 Conclusions, outlook and further work

A significant amount of *in situ* validated Sentinel-2 data has been produced from this project, along with corresponding ancillary measurements and data from other sources.

A series of main conclusions can be drawn from the project:

- Biofouling seems to affect the spectral response of FML concentrations mainly in terms of signal intensity in the RGB part of the spectrum. The red-edge, NIR and SWIR bands do not show any significant effect of biofouling in these parts of the spectrum.
- Submersion depth significantly affects the reflectance of the HDPE mesh target. A submersion of the target in the scale of 20 to 30 cm below the water surface results in 30-40% of signal decay throughout the spectral range of the MSI's sensor.
- Turbidity and wind speed were two factors that were not sufficiently assessed in this study. Turbidity was generally quite high and stable during the PLP2021 acquisition campaign, and the change in turbidity that did occur was not independent of wind speed and did not seem to have a significant effect on the HDPE target's spectral signature. Further work is required.
- FML detection is generally possible under favourable conditions, with a minimum estimated abundance fraction of less than 20% being detectable.

In order to better understand the effects that the above-described parameters have on the spectral response of FML, we have designed the PLP2022 to run for a two-months period. We plan to deploy targets in the Gulf of Gera in order to further investigate the effects of biofouling and take into account possible UV degradation that might occur. Lab spectral measurements can greatly help in assessing these effects. The gathering of biofouling samples in order to identify the biological characteristics of the biofouling organisms can also be very useful in understanding the biofouling effects on the spectral response of FML. Spectral samples before and after target deployment can allow the assessment of UV degradation effects.

Transferable know-how for further data acquisition campaigns:

- Requirements for long-term data acquisition campaigns, including anchoring system requirements, target specifications, construction and long-term deployment and potential materials.
- Identification of field-related issues that can be encountered.
- Licencing and specifications to meet maritime regulations and requirements.
- In situ data acquisition and UAS data acquisition methodologies using a variety of sensors and instruments.
- Identification of factors affecting FML detection and effect of environmental parameters on FML spectral response.
- FML detection using partial unmixing methodologies.

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